Geotech Geol Eng (2009) 27:585–593
DOI 10.1007/s10706-008-9248-6

TECHNICAL NOTE

Effect of Soil Parameters on Dynamic Cone Penetration Indices of Laterite Sub-grade Soils from India

Varghese George · Ch. Nageshwar Rao · R. Shivashankar

Received: 4 June 2008 / Accepted: 27 October 2008 / Published online: 7 November 2008

Abstract The focus of this study was on correlating the effect of grain-size, maximum dry-density (MDD), field moisture content, and the void ratios on penetration measured using the dynamic cone penetrometer (DCP) for laterite soils blended with fines. Tests were performed on soil samples compacted to MDD for moulding water contents set to the optimum moisture content (OMC), dry of OMC, and wet of OMC un-soaked condition. The results indicated that an increase in the fines-content caused a decrease in the MDD, and an increase in the OMC and the DCP penetration. Regressions were developed correlating various parameters.

Keywords DCP · Silty soil · Laterite sub-grade · Soil parameters · Correlation

1 Introduction and Need for the Study

Evaluation of the sub-grade strength and stiffness, and its monitoring is essential in the design of pavements. Monitoring of the sub-grade strength is considered to be important, as information on the behavior of the sub-grade when subjected to traffic loads over a longer period, can assist in further fine-tuning of the design-methodology. The strength and stiffness characteristics of the sub-grade influence the load carrying capacity of pavement systems (Wu and Sargand 2007). An understanding of the soil-stiffness and strength-characteristics of sub-grades will be beneficial in enforcing high-quality in construction, through effective quality control and monitoring that includes quantitative evaluation of sub-grades (Fleming et al. 1998). In this context, it may be observed that the resistance offered to penetration has been used as a measure of soil strength and stiffness from the fifteenth century onwards (Burnham and Johnson 1993). A study on the evolution of the DCP reveals that a similar proto-type of this device developed by Sir Stanford Fleming in 1872, had its origin based on the idea of using the resistance to penetration offered to the penetration of a steel rod, which later led to the development of the *ram penetrometer* by Nicholaus Goldmann, and the *Prufstab*, by Kiinzel in 1936, that was extensively used by Paproth (Burnham and Johnson 1993). Scala (1956) of Australia, gave shape to the DCP that we see in its present form. The device was standardized in 1964, and was named as the "light penetrometer" (DIN 2002).

The DCP is considered to be an effective tool for assessing in situ strength and stiffness of pavement and sub-grade (Abu-Farsakh et al. 2004). It can be

---

V. George (✉) · Ch. Nageshwar Rao · R. Shivashankar
Department of Civil Engineering, National Institute of Technology Karnataka, Srinivasnagar Post, Mangalore 575025, Karnataka, India
e-mail: varghese-2k@lycos.com

Ch. Nageshwar Rao
e-mail: nagnitk@gmail.com

R. Shivashankar
e-mail: shivashankar.surathkal@gmail.com

used to verify both the level and uniformity of compaction for the layers tested, which makes it an ideal device for quality control in pavement construction (Chen and Wang 2001), in addition to providing soil-investigators an opportunity to verify the thickness of the layers tested. This highly portable device can be easily fabricated, and is easy to operate. It can also be used in estimating the CBR values of the sub-grades (Jahren et al. 1999).

2 Problem Definition and Scope of Work

In a number of cases related to realignment, and widening of existing roads in regions with a predominance of laterite soils, road-engineers encounter situations where laterite sub-grades mixed with silty fines are required to be compacted to prepare sub-grades for new road surfaces. Also, in the field of road construction, one of the practical difficulties experienced is that, although it is required to achieve 100% relative compaction at OMC as measured using the standard proctor test, it is generally observed that the level of compaction achieved in practice is about 97% due to minor changes in water-content that tend towards 'dry of optimum' or 'wet of optimum' (Kim and Kim 2006). This is observed even in patches of pavement sub-grades that are compacted using vibratory rollers.

The present work is focused on conducting a study on the effect of intrusion of silty soils, and the effect of minor changes in field moisture-conditions on the supporting strength of laterite sub-grades. The DCP tests were performed on un-soaked remolded laterite soils blended with various percentages of silty (or *shedi*) soils on soil samples compacted to maximum dry-density (MDD) with molding moisture-contents (MMC) at the drier side of optimum (designated as M_1 for samples prepared at OMC − 3%), optimum (designated as M_2 for samples prepared at OMC), and wetter side of optimum (designated as M_3 for samples prepared at OMC + 3%).

Correlations were developed using the statistical package for social sciences (SPSS) quantifying the influence of the percentage of fines, gravel, sand, MDD, OMC, and the void ratios, on the penetration resistance of soil measured using DCP. Relationships were developed based on the logical correctness, and the need to maintain high predictive capabilities. Additionally, the relationships developed were required to satisfy the critical *R*-square values at a significance of 0.025, maintaining a high *F* test value for a confidence level of more than 95%. The study area for this investigation comprises the area close to the existing highway (NH17) in the District of Dakshina Kannada, of coastal Karnataka in peninsular India, where approximately 40% of the sub-grades available are of lateritic origin.

3 Experimental Program

Laterite soil was first excavated from a site close to National Institute of Technology Karnataka, Surathkal, India, and was labeled as B_1. This soil sample was then blended with silty soil (locally known as *shedi* soil) obtained from Kavur, a nearby locality, in various proportions, and labeled as B_2, B_3, and B_4. These blends were prepared with 25, 50, and 75% of silty soil, respectively. The original silty soil with a high percentage of fines, obtained from Kavur, was labeled as B_5. The mixing of laterite soils with silty soil (or *shedi* soil) was performed with the intention of altering the fines-content (referring to particles of size lesser than 75 μm). Table 1 shows that the percentage of fines in blends B_1 to B_5 vary from 10 to 92%.

The index properties of the laterite soils blended with various percentages of fines were first determined. The details of various blends of soils tested, and information on the specific gravity, Atterberg's limits, grain-size analysis, optimum moisture content (OMC), the D_{60}, D_{50}, and D_{10} values in millimeter, and the maximum dry-density (MDD) for various blends are provided in Table 1. The grain-size distributions for various blends are represented in Fig. 1. It can be seen that there are minor differences between theoretically calculated expected values of percentages of gravel, sand, and fines and the actual values determined using tests for grain-size analyses. This is attributed to experimental errors in the blending of soils, and the need to have performed grain-size analyses on more number of samples.

It was then planned to perform DCP tests for un-soaked remolded soil samples for three different molding moisture-conditions, viz. M_1, M_2, and M_3 in the laboratory at standard proctor density, for various blends B_1, B_2, B_3, B_4, and B_5. These tests were aimed

Table 1 Index properties of blended laterite soils

Property	B_1	B_2	B_3	B_4	B_5
Laterite:silty (shedi)	100:0	75:25	50:50	25:75	0:100
OMC (%)	12.1	13.1	15.2	19.5	24.0
MDD (kN/cu.m)	18.8	18.0	17.0	15.4	14.4
Specific gravity	2.65	2.60	2.56	2.51	2.45
Gravel (%)	33.0	29.0	20.0	11.0	2.0
Sand (%)	57.0	44.0	32.0	19.0	6.0
Fines (%)	10.0	27.0	48.0	70.0	92.0
Voids ratio	0.41	0.44	0.51	0.63	0.70
Liquid limit (%)	57.0	58.0	59.0	59.5	60.0
Plastic limit (%)	26.6	27.3	28.0	29.0	31.0
Shrinkage limit (%)	19.4	20.4	21.0	21.8	23.0
Plasticity index (%)	30.4	30.7	31.0	30.5	29.0
IS classification	SP-CH	SM	SM	CH	CH
DCPI for M_1 (mm/blow)	1.97	2.37	2.57	4.94	9.19
DCPI for M_2 (mm/blow)	2.3	2.98	4.9	7.6	11
DCPI for M_3 (mm/blow)	3.46	4.29	8.26	8.25	14.2
D_{60} (mm)	3.60	3.00	0.40	0.05	0.026
D_{50} (mm)	2.50	1.80	0.10	0.03	0.015
D_{10} (mm)	0.0800	0.0135	0.005	0.0032	0.0022

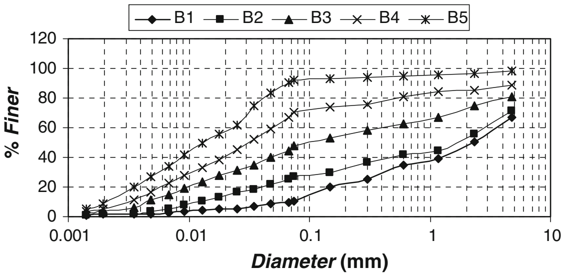

Fig. 1 Grain-size distribution for various blends

at generating simple correlations that could assist engineers in estimating the required design parameters for a wide range of soil types of the region varying from laterite to silty soils. MDD, OMC, and void ratio are important parameters that indicate the strength and stiffness of soils. The experiment aims at correlating the MDD, OMC, and the void ratio, of various blends of lateritic soils, to the penetration resistance. The investigations also include supporting statistical analyses on the influence of gravel, sand, and fines on the penetration resistance. Details on the laboratory setup for various tests performed are provided below.

4 Laboratory Test Setup for DCP and Tests on Unsoaked Soil Samples

A cylindrical test-box of 450 mm diameter and 450 mm height, made of 6 mm thick steel plates, provided with a base plate welded with 8 mm diameter mild-steel stiffeners at the bottom-side, was used to perform the investigations. An 8 mm mild-steel hoop was welded at the top opening and at bottom of the test-box to provide additional stability and stiffness, and to prevent undue deformations on load-application (see Fig. 2).

In order to perform tests on blended laterite soils at the standard proctor density, for moisture-contents M_1, M_2, and M_3, the soil required to fill the cylindrical test-box of an inner diameter of 450 mm, and a soil-depth of 350 mm was first calculated. One-fifth of the soil required was then noted, and the soil was filled in five layers, each of 70 mm thickness. The soil layers were compacted using a rammer, to a total soil-depth of 350 mm.

While conducting the DCP test, a circular plate of 200 mm diameter, with a hole of 50 mm diameter at the center, was placed at the middle of the top surface to be tested. The penetrometer had a diameter of 20 mm. A seating load was applied by allowing the hammer of 8 kg weight attached to the DCP to fall through a height of 575 mm, causing an impact on

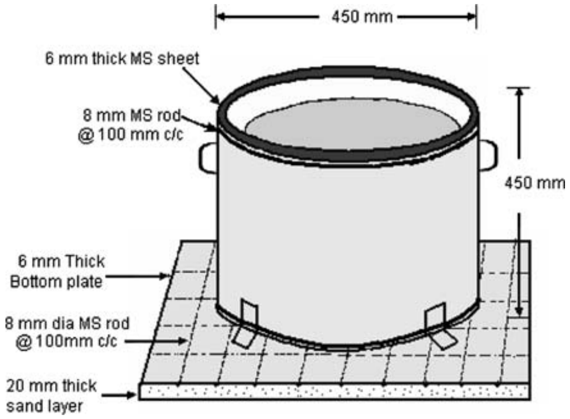

Fig. 2 Mild steel test-box fabricated

the anvil, until the widest part of the penetrating cone was just below the testing surface. The first reading before commencement of the test, was measured from the top of the circular plate to the bottom of the anvil using a steel-scale of 1 m length, graduated in millimeters. Later, the penetrations were measured for every five blows applied. The penetration test was performed for a total penetration depth of 300 mm. The observations were then tabulated. The DCP index value (*DCPI*) was obtained by dividing the total penetration in mm by the number of blows (mm/blow) and reported for each sample.

5 Results and Discussions

Based on information compiled in Table 1, the variations in the OMC, MDD, specific gravity, percentage of gravel, percentage of sand, and the percentage of fines among various blends B_1, B_2, B_3, B_4, and B_5 of laterite soils, can be represented using Fig. 3a. Also, Fig. 3b–f provide details on the compaction curves for blends B_1, B_2, B_3, B_4, and B_5 while Fig. 3g depicts variations in the MDD against the OMC for blends B_1 to B_5. It may be noted that the addition of silty fines to laterite soils in the process of blending, has resulted in the creation of blends B_1, B_2, B_3, B_4, and B_5 with fines-content content (referring to particles of size lesser than 75 µm) varying from 10 to 92%. This increase in the proportion of smaller sized particles has resulted in an increase in the total surface-area of the soil particles, consequently increasing the OMC from 12.08 to 24%.

Also, it can be observed that the increase in the percentage of fines due to blending has resulted in a corresponding decrease in the proportion of gravel and sand from 33 to 2%, and from 57 to 6%, respectively, which has caused in an increase in the void ratios. This has consequently resulted in a

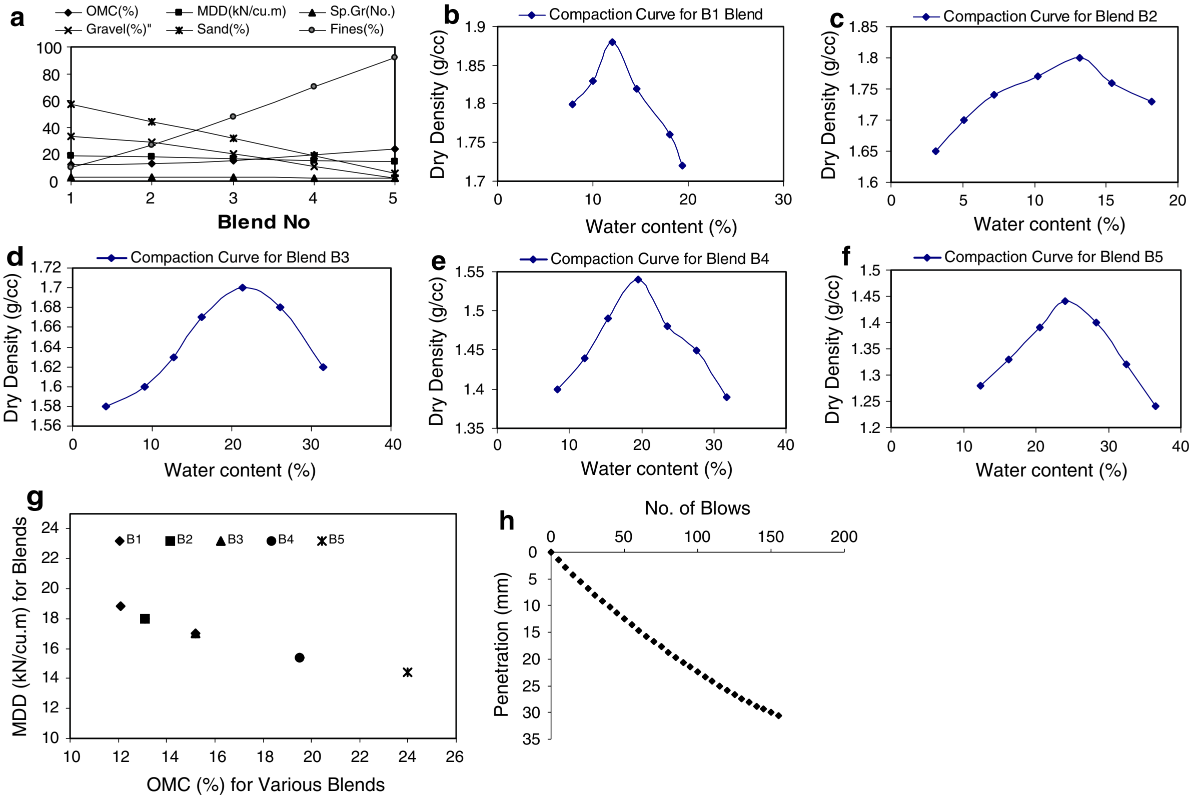

Fig. 3 **a** Effect of variations in percentages of fines on *OMC*, *MDD* and *Specific gravity*. **b** Compaction curve for Blend B_1. **c** Compaction curve for Blend B_2. **d** Compaction curve for Blend B_3. **e** Compaction curve for Blend B_4. **f** Compaction curve for Blend B_5. **g** Variations in MDD against OMC for all blends. **h** Variations in *DCPI* against penetration depth for B_1M_1 sample

decrease in the MDD from 18.8 to 14.4 kN/cu.m. Similar observations were made by Hicks and Monismith (1971) on investigations conducted on unbound granular soils. Omotosho (2004) also provides similar observations based on studies conducted on laterite soils of Nigeria. The addition of fines has also resulted in a corresponding decrease in the specific gravity from 2.65 to 2.45. Since the sample base is only about 7 diameters below the end of penetration, the plot of *DCPI* against the penetration depth was performed as shown in Fig. 3h for blend B_1 compacted to MDD at a MMC of M_1. The nature of the curve does not suggest the existence of any significant base-boundary effect.

5.1 Effect of Variations in Percentage of Fines on DCP Resistance of Soil

Based on DCP investigations performed on blended laterite soils for various blends B_1, B_2, B_3, B_4, and B_5, at moulding moisture-contents (MMC) M_1, M_2, and M_3, for un-soaked samples, the trend in variations of the *penetration index* measured in mm/blow using the DCP (*DCPI*) can be shown as in Fig. 4. Here, it may be observed that an increase in the percentage of fines from 10 to 92% for blends B_1, B_2, B_3, B_4, and B_5, has resulted in a corresponding increase in the *penetration index* from 1.97 to 9.19 mm/blow, for soil samples prepared at the MMC of M_1.

Similarly, in the case of soil samples prepared at MMCs of M_2, and M_3, the *DCPI* increased from 2.3 to 11 mm/blow, and from 3.46 to 14.2 mm/blow, respectively. These observations for un-soaked soil samples confirm that the penetration resistance, has decreased with an increase in the fines-content, indicating a significant negative influence on the stiffness of soils. Similar observations were made by Thompson and Robnett (1979), where resilient modulus values were found to be lower for soils with higher silt, and lower clay contents, as reported by Titi et al. (2006). It can be further observed that the *penetration index* for un-soaked samples ($DCPI_u$) for M_1, is lower than that for M_2, and for M_3. This is probably due to the reason that compacted drier soils have higher stiffness and offer greater resistance to penetration in the case of sandy, silty, and clayey soils when compacted to the drier side (Kim and Kim 2006) of OMC. Table 2 provides details of regression equations developed for the prediction of *DCPI* values based on variations in the percentage of fines in blended laterite soils.

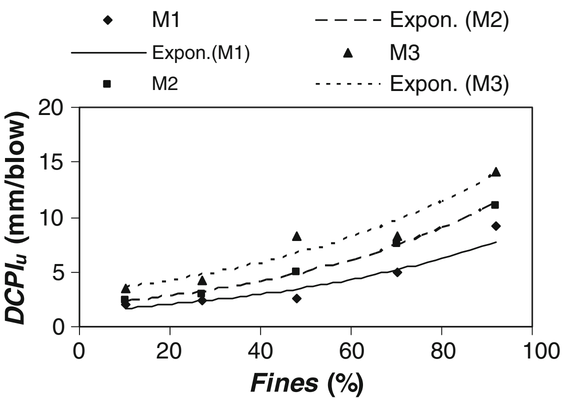

Fig. 4 Variations in percentage of fines versus *DCPI* for unsoaked conditions

5.2 Effect of Variations in Percentage of Gravel on *DCPI* of Soil

In this investigation on blended laterite soils, the effect of variations in the percentage of gravel on the *penetration resistance* was also analyzed. The increase in the proportion of silty soil from blends B_1 to B_5 resulted in a consequent decrease in the gravel content. The effect of the decrease in the percentage of gravel on the *DCPI* of blended laterite soils for un-soaked soil-conditions is illustrated in Fig. 5.

Here, the behavior of the soil sample for MMCs M_1, M_2, and M_3, when analyzed for decreasing percentages of gravel, was found to be similar to that observed, as when the fines-content was increased. Table 3 provides details of the regression equations developed for the prediction of *DCPI* values based on variations in the percentage of gravel in blended laterite soils.

5.3 Effect of Variations in Percentage of Sand on *DCPI* of Soil

The effect of variations in the percentage of sand on the penetration resistance was also studied. The increase in the proportion of silty soil from blends B_1 to B_5 resulted in a consequent decrease in the sand-content. The effect of the decrease in percentage of sand on the *DCPI* of blended laterite soils for un-soaked soil-conditions is illustrated in Fig. 6.

Table 2 Regressions for *DCPI* against percentage of *fines* (x) for unsoaked conditions

MMC	Regression equations for *DCPI* (y)	R^2	R^2adj	SEE	F	t	Sig F
M_1	$y = 1.040e^{0.048x}$	0.92	0.89	0.21	32.69	5.34	0.010
M_2	$y = 1.853e^{0.019x}$	0.99	0.99	0.05	789.2	24.8	0.001
M_3	$y = 1.586e^{0.124x}$	0.91	0.87	1.51	28.72	1.19	0.012

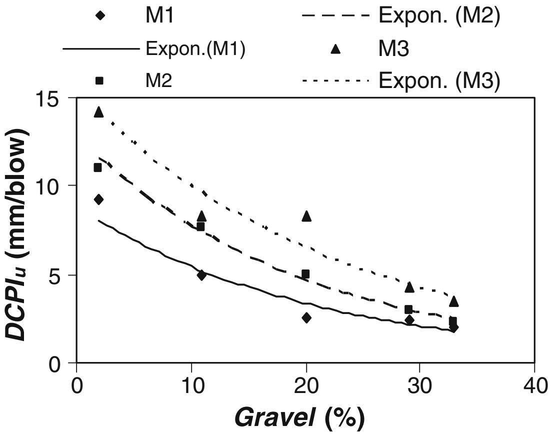

Fig. 5 Variations in percentage of gravel versus *DCPI* for unsoaked conditions

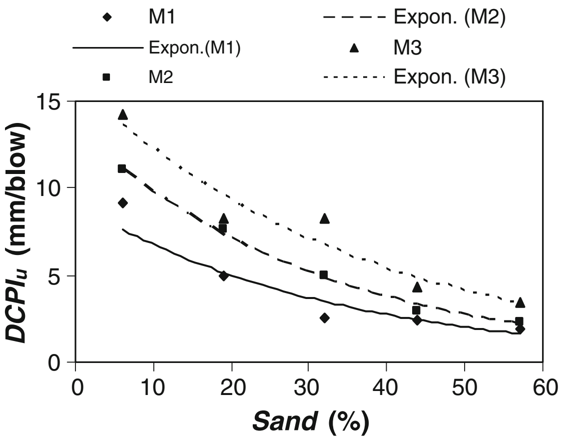

Fig. 6 Variations in percentage of sand versus *DCPI* for unsoaked conditions

It may be observed that the behavior of the soil sample for the MMCs M_1, M_2, and M_3, when analyzed for decreasing percentages of sand, was found to be similar to that observed, as when the fines-content was increased. Table 4 provides details of the regression equations developed for the prediction of *DCPI* values based on variations in the percentage of sand in blended laterite soils.

5.4 Effect of Variations in MDD on *DCPI* of Soil

The effect of variations in the MDD on the penetration resistance was also studied. The increase in the proportion of silty soil from blends B_1 to B_5 resulted in a consequent decrease in the MDD. The effect of the decrease in MDD on the *DCPI* of blended laterite soils for un-soaked soil-conditions is illustrated in Fig. 7.

Here, the behavior of the soil sample for the MMCs M_1, M_2, and M_3, when analyzed for decreasing MDD (due to increase in the percentage of fines), was found to be similar to that observed above. Table 5 provides details of the regression equations developed for the prediction of *DCPI* values based on variations in the MDD of blended laterite soils.

5.5 Effect of Variations in OMC on *DCPI* of Soil

In the above study, the effect of variations in the OMC on the penetration resistance was also analyzed. The increase in the proportion of silty soil from blends B_1 to B_5 resulted in a consequent increase in the OMC. The effect of the increase in OMC on the *penetration index* (*DCPI*) of blended laterite soils for un-soaked soil-conditions is illustrated in Fig. 8.

Table 3 Regressions for *DCPI* against percentage of *gravel* (x) for unsoaked conditions

MMC	Regression equations for *DCPI* (y)	R^2	R^2adj	SEE	F	t	Sig F
M_1	$y = 8.833e^{-0.048x}$	0.93	0.91	0.19	41.75	6.03	0.007
M_2	$y = 12.77e^{-0.05x}$	0.99	0.99	0.05	568.9	21.3	0.000
M_3	$y = 15.35e^{-0.043x}$	0.93	0.91	0.17	42.13	6.81	0.007

Table 4 Regressions for *DCPI* against percentage of *sand* (*x*) for unsoaked conditions

MMC	Regression equations for *DCPI* (*y*)	R^2	R^2adj	SEE	*F*	*t*	Sig *F*
M_1	$y = 9.136e^{-0.030x}$	0.90	0.87	0.23	26.91	4.73	0.013
M_2	$y = 13.44e^{-0.032x}$	0.99	0.99	0.07	333.89	15.71	0.000
M_3	$y = 14.02e^{-0.200x}$	0.89	0.86	1.6	24.99	9.63	0.015

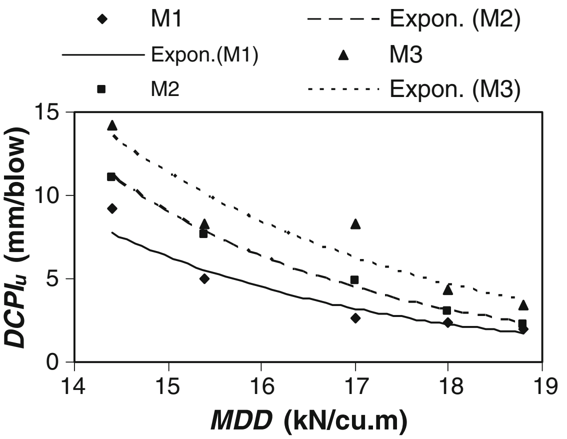

Fig. 7 Variations in MDD versus *DCPI* for unsoaked conditions

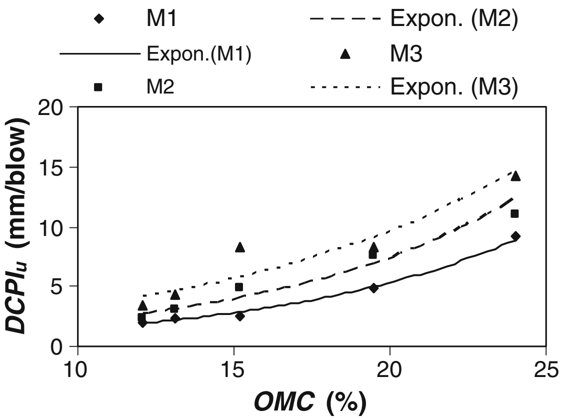

Fig. 8 Variations in OMC versus *DCPI* for unsoaked conditions

In this case, the behavior of the soil sample for the MMCs M_1, M_2, and M_3, when analyzed for increasing OMC (due to increase in the percentage of fines), was found to be similar to that observed above. Table 6 provides details of the regression equations developed for the prediction of *DCPI* values based on variations in the OMC of blended laterite soils.

5.6 Effect of Variations in Void Ratios on *DCPI* of Soil

Also, the effect of variations in the void ratios on the *penetration index* measured in terms of mm/blow was also studied. The increase in the proportion of silty soil from blends B_1 to B_5 resulted in a consequent increase in the values of the void ratios. The effect of the increase in void ratios on the *penetration index* (*DCPI*) of blended laterite soils for un-soaked soil-conditions is illustrated in Fig. 9.

Here, the behavior of the soil sample for the MMCs M_1, M_2, and M_3, when analyzed for increasing void ratios (due to increase in the percentage of fines), was found to be similar to that observed above. Table 7 provides details of the regression equations developed for the prediction of *DCPI* values based on variations in the void ratios in blended laterite soils.

6 Conclusions

The above work focused on the study of index properties of laterite soils blended with various percentages of silty soils (locally known as *shedi* soil). The investigations also dealt with a study on the

Table 5 Regressions for *DCPI* against *MDD* (*x*) for unsoaked conditions

MMC	Regression equations for *DCPI* (*y*)	R^2	R^2adj	SEE	*F*	*t*	Sig *F*
M_1	$y = 1{,}035.603e^{-0.339x}$	0.93	0.91	0.188	42.64	1.14	0.007
M_2	$y = 1{,}829.14e^{-0.354x}$	0.99	0.99	0.066	377.53	3.26	0.000
M_3	$y = 964.36e^{-0.296x}$	0.99	0.87	0.207	26.99	1.04	0.013

Table 6 Regressions for *DCPI* against *OMC* (x) for unsoaked conditions

MMC	Regression equations for *DCPI* (y)	R^2	R^2adj	SEE	F	t	Sig F
M_1	$y = 0.4086e^{0.128x}$	0.99	0.98	0.081	245.01	7.024	0.000
M_2	$y = 0.578e^{0.127x}$	0.95	0.93	0.170	54.32	3.33	0.005
M_3	$y = 1.133e^{0.1066x}$	0.86	0.82	0.243	18.72	2.33	0.022
	$y = 0.036\,x^{1.88}$	0.88	0.85	0.217	24.13	0.93	0.016

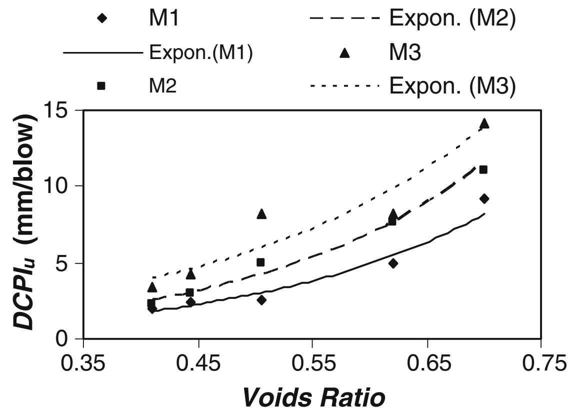

Fig. 9 Variations in voids ratio versus *DCPI* for unsoaked conditions

effect of various factors such as, the percentage of fines, gravel and sand, the MDD, OMC and the void ratios on the *DCPI* values observed, and the development of correlations among them. The following conclusions can be drawn based in this study:

1. In the investigations on the index properties of blended laterite soils, it was observed that an increase in the effective percentage of fines from 10 to 92% resulted in a corresponding increase in the OMC. This is mainly due to the increase in the total surface-area of the soil particles as the proportion of fines increases.

   Also, the increase in the proportion of fines, and the accompanied decrease in the percentage of gravel and sand for the blended laterite soil samples have resulted in an increase in the void ratios. This has consequently decreased the MDD, the penetration resistance and the average specific gravity of the soil particles. However, no notable change in Atterberg's limits was observed, since the proportion of soil fractions lesser than 425 μm has not been altered significantly due to the increase in the percentage of fines.

2. In the DCP tests conducted on un-soaked blended laterite soil samples moulded at MDD, it was observed that the *DCPI* values determined, showed an increasing trend as the moulding moisture content increased from M_1 to M_3. This strong correlation is due to the reason that compacted drier soils generally possess higher stiffness.

   Also, the strong correlation between the DCPI and the OMC, and between the DCPI and the void ratio, indicates that the penetration index increases with the increase in void ratio, following an exponential function for un-soaked blended laterite soils.

3. The nature of plot of *DCPI* values against the penetration depth did not reveal evidence of the existence of any significant base-boundary effect in the experiments with the cylindrical test-box, and the DCP.

The strength of the above conclusions can be further reinforced, by examining the coefficients of

Table 7 Regressions for *DCPI* against *Voids ratio* (x) for unsoaked conditions

MMC	Regression equations for *DCPI* (y)	R^2	R^2adj	SEE	F	t	Sig F
M_1	$y = 0.227e^{5.109x}$	0.96	0.94	0.151	67.79	2.95	0.003
M_2	$y = 0.296e^{5.233x}$	0.98	0.98	0.100	161.46	4.44	0.001
M_3	$y = 0.65e^{4.375x}$	0.89	0.85	0.218	24.01	2.04	0.016

the independent variables of the corresponding regressions developed. The correlations developed quantifying the influence of the percentage of fines, gravel, sand, the MDD, OMC, and the void ratios, on the *DCPI* values, are expected to be of use to practicing engineers. However, this study does not address the role of friction effects. It also does not attempt to correlate relative density to the *DCPI.*

References

Abu-Farsakh MY, Alshibli K, Nazzal MD, Seyman E (2004) Assessment of in situ test technology for construction control of base courses and embankments, report no. FHWA/LA.04/389, Louisiana Transportation Research Center, Baton Rouge, pp 126

Burnham T, Johnson D (1993) In situ foundation characterization using the dynamic cone penetrometer, Minnesota Department of Transportation, study no. 9PR3001, report no. 93/05, pp 2

Chen, DH, Wang, JN, Bilyeu J (2001) Application of dynamic cone penetrometer in evaluation of base and sub-grade layers, Transp Res Rec 1764, TRB, Washington, DC

DIN 4094 (2002) German standard for subsoil field investigations-part 1: cone penetration tests

Fleming PR, Rogers CDF, Frost MW (1998) Performance parameters and target values for construction of UK road foundations. Proceedings of the 5th international conference on bearing capacity of roads and airfields, vol 3, Trondheim, Norway, pp 1491–1502

Hicks RG, Monismith CL (1971) Factor influencing the resilient response of granular materials, HRB 345, Washington, DC

Jahren CT, Ellsworth BJ, Bergeson K (1999) Constructability test for cold-in-place Asphalt recycling. J Constr Eng 125(5): 325–329

Kim D, Kim RJ (2006) Resilient behavior of compacted subgrade soils under the repeated tri-axial test. Sci Direct-Constr Build Mater 21(7):1470–1479

Omotosho O (2004) Influence of gravelly exclusion on compaction of lateritic soils, geotechnical and geological engineering, vol 22. Kluwer, Netherlands, pp 351–359

Scala AJ (1956) Simple methods of flexible pavement design using cone penetrometers, Proceedings of the 2nd Australian and New Zealand conference on soil mechanics and foundation engineering, Christchurch, pp 73–83

Thompson MR, Robnett QL (1979) Resilient properties of subgrade soils. Transp Eng J ASCE 105(TE1):71–89

Titi HH, Elias MB, Helwany S (2006) Determination of typical resilient modulus values for selected soils representative of the soils distribution of Wisconsin, research report, Wisconsin Department of Transportation, Wisconsin Highway Research Program, Madison

Wu S, Sargand S (2007) Use of dynamic cone penetrometer in sub-grade and base acceptance, Ohio University, report no. FHWA/ODOT-2007/01, prepared in cooperation with the Ohio Department of Transportation Office of Research and Development and the United States Department of Transportation Federal Highway Administration, USA, pp 111